

UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES
4301 JONES BRIDGE ROAD
BETHESDA, MARYLAND 20814-4799

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Title of Thesis: Effectiveness, Suitability, and Performance testing of the SKC® Deployable Particulate Sampler as compared to the currently fielded Airmetrics MiniVol™

Name of Candidate: MAJ Steven Lee Patterson
Master of Science in Public Health
Department of Preventive Medicine and Biometrics

Thesis and Abstract Approval:

Chairman:
MAJ Timothy A. Kluchinsky, Jr., DrPH

Date

Jack M. Heller, PhD

Date

Jennifer A. Rusiecki, PhD

Date

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Steven Lee Patterson
MAJ, MS, U.S. Army
Department of Preventive Medicine and
Biometrics
Uniformed Services University of the
Health Sciences

ABSTRACT

Effectiveness, Suitability, and Performance testing of the SKC® Deployable Particulate Sampler as compared to the currently fielded Airmetrics MiniVol™

by

MAJ Steven L. Patterson, Master of Science in Public Health, 2007

Uniformed Services University of the Health Sciences

Thesis Advisor: Timothy A. Kluchinsky, Jr., DrPH,
Department: Preventive Medicine and Biometrics
Division: Occupational and Environmental Health Sciences

Epidemiological studies have linked particulate matter (PM) exposure to mortality, morbidity, cardiovascular disease in the elderly, and an increased rate of respiratory disease. In order to monitor and assess the potential PM health risk to deployed personnel, the U.S. Army must field a portable sampler which can accurately sample particles with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers ($PM_{2.5}$). The sampler must be rugged, compact, durable, and battery operated. In this study the SKC® Deployable Particulate Sampler (DPS) is compared to the currently fielded Airmetrics MiniVol™ sampler in the hot, dry environment of Yuma Proving Grounds, Arizona and the cold, wet environment of Fort Drum, New York. Ambient air $PM_{2.5}$ was collected for fourteen and thirteen days respectively in each environment using pairs of one MiniVol™ and one DPS at three locations

simultaneously. The filters were removed, and the systems maintained as needed, every 24 hours. For all measurements taken and averaged, the DPS provided a higher (though not statistically significant) 24-hour concentration and collected 4.0 times more mass than the MiniVolTM. The results for mass were significantly different. Results from our statistical analyses of concentration and mass were incorporated into a decision matrix for effectiveness (criteria: concentration and mass). Matrices for suitability (criteria: reliability, maintainability, interoperability/compatibility, training/documentation, and logistics support/safety) and performance (criteria: flow rate and size/weight) were also utilized to evaluate each of the systems. The DPS was shown to be an improvement over the MiniVolTM when evaluated for measures of effectiveness, measures of suitability, and measures of performance utilizing these matrices.

**EFFECTIVENESS, SUITABILITY, AND PERFORMANCE TESTING OF THE
SKC® DEPLOYABLE PARTICULATE SAMPLER AS COMPARED TO THE
CURRENTLY FIELDED AIRMETRICS MINIVOL™**

by

Major Steven Lee Patterson

Environmental Science Officer

United States Army

A thesis submitted to the Faculty of the Department of Preventive
Medicine and Biometrics, Uniformed Services University of the Health
Sciences in partial fulfillment of the requirements for the degree
of
MASTER OF SCIENCE IN PUBLIC HEALTH, 2007

PREFACE

This study was conducted in collaboration with the United States Army Center of Health Promotion and Preventive Medicine. It was designed to compare and analyze the effectiveness, suitability, and performance of the Deployable Particulate Sampler when compared to the MiniVolTM at the 2.5 micrometers particulate matter sampling level.

DEDICATION

I dedicate this Master of Science in Public Health thesis to my wife, Krista and my sons John Ellis and Julian Lee. Also, to my parents for providing me with the foundation to make all of this possible. Thank you all for your support and sacrifices.

-Steven

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I thank the United States Army Center for Health Promotion and Preventive Medicine for the funding, analytical, and logistical support required to complete this work. Without their assistance, this study would not have been possible.

I also thank the members of my committee for their faith and confidence in my abilities.

Special thanks to COL Robert Lipnick for supporting me when others did not.

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CHAPTER 1

INTRODUCTION

Statement of Problem

Epidemiological studies have linked exposure to particulate matter (PM) with an increased rate of respiratory disease, cardiovascular disease in the elderly, mortality, and morbidity.¹ Both acute and chronic exposures to PM have been shown to be associated with negative health impacts.¹ A study of short-term exposure to PM with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers ($PM_{2.5}$)² found an association between exposure and an increase in mortality and hospital admissions.¹

In order to better monitor the potential PM related health risk to Soldiers, the U.S. Army is exploring the possibility of fielding a new PM sampler that is rugged, compact, durable, and battery operated. Effectiveness, suitability, and performance requirements stem from (1) the potential lack of dependable power in some of the Army's operational theatres, (2) the need for the equipment to withstand a hostile environment, (3) the need to be dependable, and (4) the need to be capable of rapid deployment with military forces. Additionally, size and weight must be considered as they heavily impact the type and quantity of equipment that may be rapidly positioned into a theatre of operations.

The current PM sampling protocol for the U.S. Army calls for the collection of PM with an aerodynamic diameter less than or equal to a nominal 10.0 micrometers (PM_{10}).³ Future sampling protocols driven by Environmental Protection Agency (EPA) policies will likely require $PM_{2.5}$ sampling in lieu of or in addition to PM_{10} sampling. Therefore, validation of the recently developed SKC® Deployable Particulate Sampler's (DPS) (SKC® Inc. Eighty Four, PA) ability to meet effectiveness, suitability, and

performance requirements at the PM_{2.5} level in an operational environment is needed so that the U.S. Army's environmental science officers and preventive medicine specialists may more effectively characterize the ambient air exposure to personnel.

Background

Questions arose in the years following Operation Desert Storm regarding Service Members' exposures while serving in Iraq and Kuwait. On May 26th 1995, as a result of these concerns and a lack of current or historical environmental exposure data, the Presidential Advisory Committee on Gulf War Veteran's Illness recommended that programs be initiated to carry out environmental surveillance of Service Members during future deployments.⁴ The Deployment Occupational Environmental Health Surveillance (DOEHS) System was created in order to meet this requirement. A critical element of the DOEHS System is particulate matter air sampling.

The portable PM sampler originally chosen for use by the U.S. Army was the Airmetrics MiniVolTM portable air sampler (AirmetricsTM, Springfield, OR, USA). The MiniVolTM sampler is battery powered and capable of collecting PM_{2.5}, PM₁₀, or Total Suspended Particulates (TSP). TSP are airborne particles less than or equal to 100 micrometers. The MiniVolTM samples at a flow rate of 5.0 liters per minute (LPM) for a 24-hour time period per battery charge. The sampling fraction collected is dependent upon changing out the impactor heads for either PM₁₀, or placing the PM₁₀ and PM_{2.5} impactors in sequence to select for PM_{2.5}. To sample for TSP, the sampler is run with the inlet and filter in place without any impactors in place.

The SKC[®] DPS samples at a flow rate of 10.0 LPM for a 24-hour time period per battery charge. The sampling fraction collected is dependent upon changing out the

impactor heads for either PM₁₀, or PM_{2.5}. In its current configuration the DPS is not capable of sampling for TSP.

The United States Army Center for Health Promotion and Preventive Medicine (USACHPPM) conducted an occupational Health Hazard Assessment of the MiniVol™ and of the DPS. There were no occupational health hazards identified with either sampler provided operators, testers, and maintainers follow guidance identified in the manuals and accepted sampling protocols.^{5,6}

Research Questions

The specific aims of this research were to: (1) Collect and compare PM_{2.5} ambient air sampling data using the DPS and MiniVol™ systems, (2) Evaluate effectiveness of both systems in cold weather and desert environments via decision matrices based on Department of Defense acquisition guidance (3) Evaluate suitability of both systems in cold weather and desert environments via decision matrices based on DOD 5000 series acquisition guidance, (4) Evaluate performance of both systems in cold weather and desert environments via decision matrices based on DOD 5000 series acquisition guidance.⁷

Definition of Terms

Aerodynamic Diameter - the diameter of a spherical water droplet that settles at the same constant velocity as the particle being sampled.³

Airmetrics MiniVol™ Portable Air Sampler - battery-operated, portable particulate sampler manufactured by Airmetrics™, Springfield, OR, USA.

Chromosomal Aberration (CA) - Any type of change in the chromosome structure or number (deficiencies, duplications, translocations, inversions, etc.). Although it can be a mechanism for enhancing genetic diversity, such alterations are usually fatal or ill-adaptive, especially in animals.⁸

Deployment Occupational Environmental Health Surveillance (DOEHS) System - a multi-component system to sample soil, water, and ambient air established to provide environmental exposure data for Soldiers deployed outside of the United States.

Effectiveness - The extent to which the goals of the system are attained, or the degree to which a system can be elected to achieve a set of specific mission requirements. Also, an output of cost-effectiveness analysis.⁹

Hold Time - Time between collecting a sample and the analysis of the sample.

Mean Time Between Failure (MTBF) – For a particular interval, the total functional life of a population of an item divided by the total number of failures (requiring corrective maintenance actions) within the population. The definition holds for time, rounds, miles, events, or other measures of life unit. A basic technical measure of reliability recommended for use in the research and development contractual specification environment, where “time” and “failure” must be carefully defined for contractual compliance purposes.⁹

Millibars (mb) - unit of atmospheric pressure, 1mb is equal to 100Pa. Standard atmospheric pressure is about 1000mb.

Mitotic Index (MI) - In a population of cells, the ratio of the number of cells undergoing mitosis (cell division) to the number of cells not undergoing mitosis.¹⁰

Particulate Matter 2.5 (PM_{2.5}) - particulate matter with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers.¹

Particulate Matter 10 (PM₁₀) - particulate matter with an aerodynamic diameter less than or equal to a nominal 10.0 micrometers.³

Performance - Those operational and support characteristics of the system that allow it to effectively and efficiently perform its assigned mission over time. The support characteristics of the system include both supportability aspects of the design and the support elements necessary for system operation.⁹

Polycyclic Aromatic Hydrocarbons (PAH) - polycyclic aromatic hydrocarbons are the class of hydrocarbon compounds whose molecular structure includes two or more aromatic rings.¹¹

Suitability - having the properties that are required for a specific purpose.

SKC® Deployable Particulate Sampler (DPS) System - compact, battery-operated, portable particulate sampler manufactured by SKC® Inc, Eighty Four, PA, USA.

Total Suspended Particulates (TSP) - airborne particles less than or equal to 100.0 micrometers.

Volatile Organic Compounds (VOC) - any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.¹²

Research Goal

The goal of this research was to conduct effectiveness, suitability, and performance testing of the SKC® DPS system as compared to the currently fielded MiniVol™ Portable Air Sampler at the PM_{2.5} level to determine the potential for the DPS to replace the MiniVol™ sampler.

Limitations of Study

Destructive testing of the systems to evaluate their ability to withstand drops, physical impacts, and damage was not plausible due to budget constraints. Lack of this testing minimizes the ability to quantitatively determine the durability of both systems.

An EPA compendium reference method (i.e. gold standard) to compare the two systems at the PM_{2.5} level was not available to conduct a side by side comparison to a reference method. In the absence of a comparative compendium method, the concentrations determined by the samplers could only be compared to one another.

The PM weight was determined using a Mettler MT5 microbalance (Mettler-Toledo, Inc., 1900 Polaris Parkway, Columbus, OH). The MT5 has accuracy limitations of (+/-) 0.015 mg and may mask a true difference in the data. Additionally, handling filters in a field environment may cause contamination or damage reducing the confidence level.

Fluctuations of humidity and temperature within the filter conditioning chamber may impact the confidence of the filter weights as even a small variance in the chamber humidity may have a significant impact on the filter weights.

Testing in a field environment versus a controlled environment reduces the ability to control for many of the challenging parameters presented to the systems, i.e. - wind

speed, temperature, humidity, atmospheric pressure, and PM concentration. Filter hold time requirements for volatile organic compounds (VOC) could not be met as sampling was conducted at isolated sites. Consequently, the DPS and MiniVolTM systems were not evaluated for their ability to capture and hold VOC.

CHAPTER 2

LITERATURE REVIEW

PM_{2.5}

PM_{2.5} has been linked to respiratory diseases, mortality, and cardiovascular disease in elderly individuals¹. Research has also shown that the particulate matter may display estrogenic characteristics and contain polycyclic aromatic hydrocarbons compounds (PAH) and tetrachlorodibenzo-p-dioxin 2,3,7,8 (TCDD).¹³

Recent research has shown sand dust storm PM_{2.5} and its extracts can increase clastogenic activity.¹⁴ An increase of concentration increased the occurrence of chromosomal aberration (CA) and mitotic index (MI) values declined in a dose-response manner.¹⁴ Chemical analyses of PM_{2.5} samples found the main fractions of solvent extractable organic compounds in Asian dust storms to be n-alkanes, PAHs and fatty acids.¹⁶ It has also been proposed that chemical composition of sand dust storm PM_{2.5}, and microorganisms such as fungi and bacteria attached to the particles, contribute to pulmonary inflammation.¹⁵

The majority of studies measuring PM_{2.5} and related health effects are from Asia. The greatest contributors of PM_{2.5} samples taken in China in regards to mass (in descending order) are organic carbon, sulfate, elemental carbon, sulfur, potassium, silicon, chloride, ammonium, calcium, and iron. Burning of coal and biomass is a major contributor to PM_{2.5}.¹⁷

With the current deployment situation of the U.S. Army it is important for us to be able to characterize possible exposures that the Soldiers may be exposed to during

their overseas tours. This is of particular interest in areas where there are natural threats in the form of sand storms combined with the anthropogenic threats of the area.

Airmetrics MiniVol™ Sampler

The MiniVol™ PM sampler was developed by Airmetrics™ in collaboration with the EPA and the Lane Regional Air Pollution Authority to create a portable air sampler. It was designed to collect PM_{2.5}, PM₁₀, and TSP with a flow rate of 5.0 LPM for a 24-hour period per full battery charge.

The basic MiniVol™ consists of a pump unit, a mounting cradle, preseparators/cassette filter holder assemblies (2), rechargeable batteries (2), operation manual, spare parts kit, and 12-volt battery charger.²¹ It is sold in 2 plastic carrying boxes and reconfigured by the Army into 1 large Hardigg Storm® case (Hardigg Industries, Inc., South Deerfield, MA) for deployment. Additional accessories that must be included with the system are a Y-bracket for pole mounting, impactor grease, naptha solvent, cotton cleaning swabs, flow calibrator, calculator, Kestrel® pocket wind meter (Nielsen Kellerman, Boothwyn, PA), and sampling filters.

In a one-year field test consisting of 1574 sampling events in Southeastern Kansas, the MiniVol™ had a successful sampling rate of 93 percent and a successful operating rate of 96 percent. Nineteen failures (1.2%) occurred at temperatures below 0 degrees Celsius. Anecdotal data suggest that this failure rate was reduced after desiccant packets were inserted into the sampler case. Sixty-eight mechanical failures (4.3%) were experienced during the study. Thirty-nine samples (2.5%) were discarded as a result of

contamination by insects reaching the filter and nine samples (0.6%) were eliminated due to operator error.¹⁸

The Kansas MiniVolTM samples were statistically similar when compared to a co-located MiniVolTM ($r^2 = 0.96$ for PM₁₀ and $r^2 = 0.95$ for PM_{2.5}). The MiniVolTM also provided statistically similar results when compared to a Versatile Air Pollution Sampler (VAPS) ($r^2 = 0.83$ for PM₁₀ and $r^2 = 0.85$ for PM_{2.5}). Additionally, the MiniVolTM produced similar results when compared to a continuous PM₁₀ Tapered Element Oscillating Microbalance (TEOM) monitor ($r^2 = 0.90$). Wind speed impacted the sampling efficiency of the MiniVolTM system by 10 percent at 8 km/h and more than 25 percent at 24 km/h. Field blanks indicated that the MiniVolTM system passively collected during non-sampling periods, especially for PM₁₀.¹⁸

When the MiniVolTM was compared to a TEOM[®] 1400a (Thermo Fisher Scientific, East Greenbush, NY) and a Partisol 2000[®] (Thermo Fisher Scientific, East Greenbush, NY) the following linear regression results were found: TEOM[®] 1400a = $11.018 + 0.2754 \text{ MiniVol}^{\text{TM}}$, R = 0.50, n = 13, $0.10 < p < 0.05$, and, Partisol 2000[®] = $9.5795 + 0.4964 \text{ MiniVol}^{\text{TM}}$, R = 0.55, n = 13, $p < 0.05$. The researchers experienced significant mechanical problems with the MiniVolTM and questioned the inclusion of its data in the national database of the United Kingdom.¹⁹ The low n values were due to mechanical failures with the equipment. The low R values show that the equipment did not correlate well when compared to the Partisol 2000[®] or the TEOM[®] 1400a.

The MiniVolTM system correlated well (R = 0.97, n = 18) in a 33-day indoor PM₁₀ test of the MiniVolTM compared to a BGI Inc PQ100 gravimetric sampler with a U.S.

EPA certified Graseby Anderson PM₁₀ inlet. However, the MiniVol™ over sampled by 23 percent on average and had a volumetric flow rate 4.2 percent lower than expected.²⁰

SKC® DPS System

Independent published reports regarding the DPS could not be found as a result of its recent development. The information noted below was obtained from manuals, posters, and sales literature produced by the manufacturer.

The SKC® DPS System is a compact, battery-operated, and portable particulate sampler that allows for sampling indoor or outdoor environments. The system consists of the Leland Legacy® Sample Pump, DPS Impactor, connecting tubing, mounting bracket, the impactor cap, spare filter cassette, Laminar flow meter with battery pack, battery charger, calibration adapter, impaction substrate disks, and a filter cassette opener.

The entire system is contained in a Pelican™ case (Pelican™ Products, Inc., Torrance, CA) and is designed to operate secured inside the case after set-up is complete.

The system can sample for 24 hours at 10.0 LPM on a full battery charge. It is capable of sampling either PM_{2.5} or PM₁₀ by changing out the impactor inlet. In its current configuration it is not capable of sampling for TSP.²²

CHAPTER 3

MANUSCRIPT

Manuscript

The following chapter entitled *Performance, effectiveness, and suitability testing of the SKC® Deployable Particulate Sample as compared to the currently fielded Airmetrics MiniVol™* is a manuscript intended for peer reviewed publication. This manuscript evaluates the two systems in a field environment and discusses their capabilities and challenges while taking into account the Army Acquisition Policy. This evaluation will assist in determining which attributes are deemed more beneficial in fulfilling the U.S. Army's ambient air sampling device requirement needs.

Effectiveness, Suitability, and Performance testing of the SKC® Deployable Particulate Sampler as compared to the currently fielded Airmetrics MiniVol™

¹Steven L. Patterson, ²Joseph B. Sutphin, ²Jack M. Heller, ¹Jennifer A. Rusiecki, ¹Steven L. Barnes, ^{1,2}Timothy A. Kluchinsky, Jr ., ¹Uniformed Services University of the Health Sciences, Department of Preventive Medicine and Biometrics, Bethesda MD, ²United States Army Center for Health Promotion and Preventive Medicine, Aberdeen MD.

*Corresponding Author

ABSTRACT: Epidemiological studies have linked particulate matter (PM) exposure to mortality, morbidity, cardiovascular disease in the elderly, and an increased rate of respiratory disease. In order to monitor and assess the potential PM health risk to deployed personnel, the U.S. Army must field a portable sampler which can accurately sample particles with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers (PM_{2.5}). The sampler must be rugged, compact, durable, and battery operated. In this study the SKC® Deployable Particulate Sampler (DPS) is compared to

the currently fielded Airmetrics MiniVol™ sampler in the hot, dry environment of Yuma Proving Grounds, Arizona and the cold, wet environment of Fort Drum, New York. Ambient air PM_{2.5} was collected for fourteen and thirteen days respectively in each environment using pairs of one MiniVol™ and one DPS at three locations simultaneously. The filters were removed, and the systems maintained as needed, every 24 hours. For all measurements taken and averaged, the DPS provided a higher (though not statistically significant) 24-hour concentration and collected 4.0 times more mass than the MiniVol™. The results for mass were significantly different. Results from our statistical analyses of concentration and mass were incorporated into a decision matrix for effectiveness (criteria: concentration and mass). Matrices for suitability (criteria: reliability, maintainability, interoperability/compatibility, training/documentation, and logistics support/safety) and performance (criteria: flow rate and size/weight) were also utilized to evaluate each of the systems. The DPS was shown to be an improvement over the MiniVol™ when evaluated for measures of effectiveness, measures of suitability, and measures of performance utilizing these matrices.

This manuscript has been completed in partial fulfillment of the degree of Master of Science in Public Health, Department of Preventive Medicine and Biometrics, Uniformed Services University of the Health Sciences, Bethesda, Maryland. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the United States Department of Defense or the Uniformed Services University of the Health Sciences.

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INTRODUCTION

Epidemiological studies have linked exposure to particulate matter (PM) with an increased rate of respiratory disease, cardiovascular disease in the elderly, mortality, and morbidity (Samet *et al.*, 2000). Both acute and chronic exposures to PM have been shown to be associated with negative health impacts (Samet *et al.*, 2000). A study of short-term exposure to particulate matter with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers (PM_{2.5}) (EPA, 40 Code of Federal Regulations 50 app. N, 2005) found an association between exposure and an increase in mortality and hospital admissions (Samet *et al.*, 2000).

In order to better monitor the potential PM_{2.5} related health risk to Soldiers, the U.S. Army is exploring the possibility of fielding a new PM_{2.5} sampler that is rugged, compact, durable, and battery operated. Effectiveness, suitability, and performance requirements for such a system stem from (1) the potential lack of dependable power in some of the Army's operational theatres, (2) the need for the equipment to withstand a hostile environment, (3) the need to be dependable, and (4) the need to be capable of rapid deployment with military forces. Additionally, size and weight of the instrument must be considered as they heavily impact the type and quantity of equipment that may be rapidly positioned into a theatre of operations.

Current PM sampling protocol for the U.S. Army calls for the collection of PM with an aerodynamic diameter less than or equal to a nominal 10.0 micrometers (PM₁₀) (EPA, 40 Code of Federal Regulations 50 app. B, 2005). Future sampling protocols will likely require PM_{2.5} sampling in lieu of or in addition to PM₁₀ sampling. This change to protocol will be driven by pending EPA decisions. Therefore, validation of the recently

developed SKC® Deployable Particulate Sampler's (DPS) (SKC® Inc. Eighty Four, PA) ability to meet effectiveness, suitability, and performance requirements at the PM_{2.5} level in an operational environment is needed so that the U.S. Army's environmental science officers and preventive medicine specialists may more effectively characterize the ambient air exposure to personnel.

Background

Questions arose in the years following Operation Desert Storm regarding Service Members' exposures while serving in Iraq and Kuwait. On May 26th 1995, as a result of these concerns and a lack of current or historical environmental exposure data, the Presidential Advisory Committee on Gulf War Veteran's Illness recommended that programs be initiated to carry out environmental surveillance of Service Members during future deployments (National Science and Technology Council, 1998). The Deployment Occupational Environmental Health Surveillance (DOEHS) System was created in order to meet this requirement. A critical element of DOEHS is particulate matter air sampling.

The portable PM sampler originally chosen for use by the U.S. Army was the Airmetrics MiniVol™ portable air sampler (Airmetrics™, Springfield, OR, USA). The MiniVol™ sampler is battery powered and capable of collecting PM_{2.5}, PM₁₀, or Total Suspended Particulates (TSP). TSP are airborne particles less than or equal to 100 micrometers. The MiniVol™ samples at a flow rate of 5.0 liters per minute (LPM) for a 24-hour time period per full battery charge. The sampling fraction collected is dependent upon changing out the impactor heads for either PM₁₀, or placing the PM₁₀ and PM_{2.5}

impactors in sequence to select for PM_{2.5}. To sample for TSP, the sampler is run with the inlet and filter in place without any impactors in place.

The SKC® DPS samples at a flow rate of 10.0 liters per minute (LPM) for a 24-hour time period per full battery charge. The sampling fraction collected is dependent upon changing out the impactor heads for either PM₁₀, or PM_{2.5}. In its current configuration it is not capable of sampling for TSP.

Medical Impact of PM Exposure

Epidemiologic studies link exposure to PM to morbidity and mortality in populations (primarily the elderly or those with pre-existing respiratory disease) (Samet *et al.*, 2000). The most toxic PM comes from urban sites with high contributions from anthropogenic sources (Seagrave *et al.*, 2006). Morbidity attributed to PM was investigated by comparing a population's exposure to hospital admission rates. PM_{2.5} from motor vehicle exhaust had a significant effect on hospital admission rates for a subset of respiratory diagnoses (asthma, bronchitis, chronic obstructive pulmonary disease, pneumonia, upper respiratory tract infection) and no effect on hospitalization for non-respiratory conditions (Buckeridge, Glazier, Harvey, Escobar, Amrhein, and Frank, 2002). PM's estimated effect on morbidity is an approximate 1 percent increase in admissions for cardiovascular disease and about a 2 percent increase in admissions for pneumonia and chronic obstructive pulmonary disease for each 10 ug/m³ increase in PM₁₀ (Samet *et al.*, 2000).

In a prospective cohort study of 65,893 postmenopausal women without previous cardiovascular disease, long-term exposure to fine particulate air pollution was associated

with an increased risk for cardiovascular events. It was estimated that a 76 percent increase in risk was experienced for each 10 ug/m^3 increase in long-term exposure to $\text{PM}_{2.5}$ (Miller *et al.*, 2007). Also, for each 10 ug/m^3 increase of exposure, cerebrovascular risk increased 35 percent and the risk of death from a cerebrovascular event increased 83 percent (Miller *et al.*, 2007). However, the mechanism by which PM causes these negative effects is currently not well understood and is a topic of much speculation and study (Miller *et al.*, 2007).

Increased mortality is associated with elevated levels of PM exposure. Total mortality due to cardiovascular events and lung cancer were positively associated with ambient $\text{PM}_{2.5}$ concentrations (Laden, Eschenroader, Smith, and Garshick, 2006). PM's estimated effect on mortality is an approximate 0.5 percent increase in overall mortality for every 10 ug/m^3 increase in PM_{10} measured the day before death (Samet *et al.*, 2000).

In a study conducted by exposing rats to $\text{PM}_{2.5}$ and then characterizing the contaminants within the $\text{PM}_{2.5}$ it was determined that the most toxic samples were those which contained the most diesel and gasoline emissions. The wood smoke contribution in these samplers was only weakly correlated with toxicity. The mechanism of negative effect was not determined (Seagrave *et al.*, 2006).

Experiments have revealed possible biological mechanisms through which PM could cause cardiovascular disease and or illness. A possibility is that PM causes pulmonary and systemic oxidative distress and inflammation caused by the components of the PM. This could in turn create other physiological responses that would create a cardiovascular event, i.e.- thrombosis, cardiac dysrhythmias, and plaque instability (Brook *et al.*, 2004).

Little is known about the PM health effects on military populations. A study on the respiratory health status of Australian veterans of the 1991 Gulf War (exposed to oil fire smoke and dust storms) revealed an increase in self-reported respiratory symptoms, asthma, and bronchitis but did not reflect poor lung function (Kelsall *et al.*, 2004). In another study, air quality did not significantly correlate with the occurrence of emergency department visits for asthma in a population of military basic trainees in San Antonio, Texas (Letz and Quinn, 2005). Current combat military operations include exposure to vehicle exhaust in locations subject to high levels of PM, primarily from dust storms. Dust storm PM could increase pulmonary inflammation and injury (Lei, Chan, Wang, Lee, and Cheng, 2004) and may increase chromosomal aberration frequency (Aili and Meng, 2006).

Additional studies of military populations exposed to elevated levels of PM may provide an opportunity to determine the correlation of PM exposure to adverse health effects in this generally healthy group. In order to link these exposures to possible future illness we must minimize exposure misclassification by utilizing the best equipment available that meets the current mission requirements.

METHODS

The 47mm Whatman quartz QMA filters (Whatman International LTD, Maidstone, England) were conditioned for a minimum of 24 hours in a climate controlled chamber (70° F \pm 5° and 32% relative humidity \pm 5%) in accordance with EPA Compendium Method 10-3.1, *Selection, Preparation, and Extraction of Filter Material*, prior to being weighed on a Mettler MT5 micro balance (Mettler-Toledo, Inc., 1900 Polaris Parkway, Columbus, OH). Filters were again conditioned and weighed in the

same chamber and upon the same micro balance at the completion of sampling. All final filter weight values were adjusted to correct for a difference in chamber conditions and to correlate them to the difference seen in the blanks. Yuma Proving Grounds test site filters were adjusted by adding 0.025 micrograms and Fort Drum test filters were adjusted by adding 0.007 micrograms to the final filter weights.

Samplers were deployed at Yuma Proving Grounds, Arizona and at Fort Drum, New York. These sites were selected for their seasonally hot weather and cold weather environments.

Yuma Proving Grounds testing was conducted September 7th-20th, 2006 for 14 days. Average temperature during this test period was 85.1° F (low 62°, high 103°). Measurable precipitation occurred on 2 days. Average atmospheric pressure was 992.7mb.

Fort Drum testing was conducted November 7th-20th, 2006 for 13 days. Average temperature during this test period was 40.2° F (low 0°, high 63°). Measurable precipitation occurred on 9 days. Average atmospheric pressure was 1017.5mb.

Three locations were selected for sampling at Yuma Proving Grounds and Fort Drum based on their potential to provide a viable PM_{2.5} sample. Samplers were deployed in pairs with one DPS and one MiniVolTM co-located at each site. The samplers were affixed to existing utility poles at an average impactor height of 73.5 inches with an average distance of 30.6 inches between the sampler heads (Figure 3-1 and 3-2). Each sampler was mounted with the bracket(s) provided by their manufacturer.

Samplers were deployed in the morning hours at each location and were run for 24 hours. The filters were changed out every 24 hours and the samplers cleaned and

maintained as required. Batteries or systems were exchanged as appropriate for that system.

Statistical Analyses

For both the MiniVol™ and DPS, mean concentrations and standard deviations were calculated for all measurements taken at both locations; for Fort Drum alone, for Yuma Proving Grounds alone, and for each sub-location.

We used paired t-tests, Pearson Correlation Coefficients (R^2), and Intraclass Correlation Coefficients (ICCs) to compare the concentrations and mass of PM_{2.5} collected by the two samplers (Tables 3-1 and 3-2). Thus, to estimate the inter-sampler reliability we used the ICC. There is no p-value associated with these ICCs. A significance level of 0.05 was selected for t-tests and correlation coefficients. The data was analyzed using Statistical Package for the Social Sciences (SPSS) for Windows.

In order to evaluate the samplers for use by the Army, four decision matrices were constructed utilizing Army Acquisition Policy evaluation criteria of effectiveness, suitability, and performance. The matrix for effectiveness incorporated statistical elements of concentration and mass from our actual measurements. The suitability matrix was based on reliability, maintainability, interoperability/compatibility, training/documentation, and logistics support/safety. The performance matrix incorporated quantitative elements of flow rate and size/weight from our actual measurements. The fourth matrix was created to summarize the three criteria into one final matrix.

Weighting values using a 0.0 - 1.0 scale were assigned to each criteria in each matrix, post consultation with the Manager of the Deployment Data Archiving and Policy Integration Program, U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), on 20 December 2006. The assigned weighting value reflects the criteria's importance in the samplers' ability to complete the Army's sampling mission. The higher the weighting value, the higher the importance of that criteria. Each sampler was then given a score on a scale of 1-5 for its ability to perform each criteria. The higher this score the more capable the sampler is to execute the mission. The weighting values and score values for each sampler were then multiplied and summed to give a total value for each system in each category. The decision matrices are presented in Tables 3-3 (Effectiveness), 3-4 (Suitability), 3-5 (Performance), and 3-6 (Final decision matrix).

RESULTS AND DISCUSSION

Averaging all measurements of concentration at both locations (Yuma Proving Grounds and Fort Drum) and all sub-locations, we found no significant difference between means for the MiniVol™ and DPS (Table 3-1). The correlation coefficient was weak ($R^2 = 0.27$), and not statistically significant. The ICC was low (0.20). These results indicate that for all samples averaged, there was little difference between the two systems, however, combining all the measurements introduces heavy confounding from variables for which we cannot control in more complex models, so it is appropriate to analyze the data separately for each location and even for each sub-location. It should also be noted that without a compendium method to compare the samples to it is not possible to determine which one provided the more accurate concentrations.

When we evaluated the data after separating it into the two locations we found that the samplers' concentration values were not significantly different (Table 3-1). The correlation coefficients were weak ($R^2 = 0.21$ for Yuma Proving Grounds and $R^2 = 0.45$ for Fort Drum) and statistically significant only at Fort Drum ($p = 0.01$). The ICCs were low (0.11 at Yuma Proving Grounds and 0.44 at Fort Drum).

When further separated into sub-locations we found no significant differences between means for the MiniVolTM and DPS (Table 3-1). The correlation coefficients were weakest at Laguna ($R^2 = -0.1$) and strongest at Inn ($R^2 = 0.67$).

Averaging all measurements of mass at both locations (Yuma Proving Grounds and Fort Drum) and all sub-locations, we found a significant difference between means for the MiniVolTM and DPS (Table 3-2). The correlation coefficient was weak ($R^2 = 0.07$), yet was statistically significant. The ICC was low (0.13). These results indicate that for all samples averaged, there was a difference between the two samplers.

When we evaluated the data after separating it into the two locations, we found that the samplers' mass values were significantly different (Table 3-2). The correlation coefficients were very weak ($R^2 = 0.09$ for Yuma Proving Grounds and $R^2 = 0.19$ for Fort Drum) and not statistically significant. The ICCs were low (0.09 at Yuma Proving Grounds and 0.26 at Fort Drum).

When further separated into sub-locations we found significant differences between means for the MiniVolTM and DPS at all sub-locations (Table 3-2). The correlation coefficient was weakest at Laguna ($R^2 = 0.02$) and strongest at Inn ($R^2 = 0.43$). No correlation coefficients were significant. The ICC was lowest at Landfill (0.04) and highest at Inn (0.61).

We utilized the results of these statistical analyses to construct our decision matrix for effectiveness (Table 3-3). For the 24-hour average concentration category, we assigned a score of (2) to both the DPS and the MiniVolTM because they were not statistically different and neither were an EPA compendium method. For the mass criteria, we assigned a score of (3) to the DPS and a score of (2) to the MiniVolTM because the DPS consistently provided higher mass concentrations even when adjusted for flow rate. Our final value for the measure of effectiveness for the DPS was (2.4), which was greater than that of the MiniVolTM value of (2.0).

The following categories compose the decision matrix for suitability (Table 3-4): reliability - we assigned a score of (4) to the DPS and (2) to the MiniVolTM because the DPS had a much lower mean time between failure rate (MTBF) (1:997 hours for the DPS vs. 1:153 hours for the MiniVolTM) (Table 3-7); maintainability - we assigned a score of (5) to the DPS and (3) to the MiniVolTM because the DPS does not require a thorough cleaning with solvents at each filter change and is almost maintenance-free when compared to the MiniVolTM; interoperability/compatibility - both systems were assigned a score of (4) because both are equally capable in this category; training/documentation - both systems were assigned a score of (3) because the manuals will need improvement. The DPS, as a new system will require relatively uncomplicated initial/introductory training be conducted while the MiniVolTM, as an older and complicated system, will require continuous training to maintain Soldier proficiency; logistics support/safety - we assigned a score of (4) to the DPS and a (3) to the MiniVolTM because the DPS has the advantage of not requiring a solvent for its cleaning. The solvent is an identified safety risk, is often difficult to obtain at remote locations, and is difficult to ship because of its

hazardous nature. Both systems do require items that are not in the normal Army supply chain (e.g. unique batteries, PM filters, impactor grease or pre-greased disks) and may present challenges when not readily available.

The following categories compose the decision matrix for performance (Table 3-5): flow rate category - we assigned a score of (4) to the DPS and (2) to the MiniVolTM because the DPS has twice the flow rate and the flow rate of the DPS approaches the model respiratory rate of the average person ($15.2 \text{ m}^3/\text{day}$); size/weight category - we assigned a score of (4) to the DPS and (2) to the MiniVolTM because the DPS is smaller (1776 in^3 vs. 7560 in^3) and lighter (14 lbs vs. 68 lbs) than the MiniVolTM.

Our final matrix (Table 3-6) shows that the DPS system reflects an advantage when compared to the MiniVolTM using the decision matrices for effectiveness, suitability, and performance. The DPS receives a score of (3.5) versus the MiniVolTM score of (2.2) out of a possible score of (5.0).

Below we describe additional characteristics which lend evidence to the conclusion that the DPS is the better PM_{2.5} sampler based on the U.S Army's weighting of categories of measures of effectiveness, suitability, and performance.

Costs

The cost of the systems is comparable, \$2800 for a DPS and \$2990 for a MiniVolTM. However, due the frequent shipping of the systems around the world via commercial carrier the reduced weight of the DPS has been estimated to save the Army approximately \$83,000 per year in shipping expenses (Sutphin, 2005).

Flow Rate

The DPS has a flow rate advantage because its increased flow rate of 10 LPM ($14.4 \text{ m}^3/\text{day}$) approaches the USEPA recommended $15.2 \text{ m}^3/\text{day}$ as a daily average exposure inhalation rate (Sutphin, 2005). The MiniVolTM has an average daily flow rate of $6.5 \text{ m}^3/\text{day}$. This increased flow rate and a less obstructed intake system resulted in the DPS collecting 3.8 times more mass at Fort Drum and 4.3 times more mass at Yuma Proving Grounds than the MiniVolTM system. This increased mass could allow laboratories to detect contaminants on future filters that would normally produce a result of below the lower detection limit(s).

Sample Mass

The difference in mass collection by the systems is not proportional to the flow rate difference. This could be due to the decreased impaction speed created by the MiniVolTM two impactor design which allows for less particle capture during sampling or insufficient impaction force that allows for loss before the samples are weighed. The DPS system's use of an inlet with nozzles, pre-greased impaction substrate, and filter cassette may allow for more effective and uniform particle capture.

Deployment

The deployment of the DPS by a single individual is much easier than that of the MiniVolTM. The bracket system required to support the MiniVolTM weight requires installation using ratchet straps and has a tendency to twist under pressure. Also, this bracket system is rather limited to mounting onto a large utility type pole. The DPS

bracket can be easily taped, nailed, or screwed to various platforms since it must only hold the impactor head and not the entire system. The reduced weight of the DPS is also an obvious advantage if operating alone.

Battery Operation

The DPS is currently shipped with one battery installed into the unit and current Army policy is to not exchange the battery with a fresh one as needed. This results in two complete systems being needed if continuous monitoring is required for a site.

Maintenance

The maintenance of the DPS was also improved by the fact that no naptha solvent is required to clean the impactor heads due to its design and its use of a disposable grease impactor disk. The MiniVolTM impactor heads required cleaning with a solvent every 24-hours. Additionally, the naptha solvent is a hazardous substance requiring special shipping precautions and is a known skin and eye irritant (Material Safety Data Sheet, 2007).

CONCLUSION

The DPS reflects an advantage over the MiniVolTM when evaluated for measures of effectiveness, sustainability, and performance utilizing the decision matrices. The DPS obtained a higher score in all three of these measures and therefore appears to be the better choice of the two samplers being tested for U.S. Army deployment.

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Figure 3-1. Deployable Particulate Sampler (Left) and MiniVolTM (Right) operating at Yuma Proving Grounds, Arizona, September, 2006.



Figure 3-2. MiniVol™ (Left) and Deployable Particulate Sampler (Right) operating at Fort Drum, New York, November, 2006.

Table 3-3. Decision matrix for effectiveness of the Deployable Particulate Sampler and the MiniVol™.

Criteria: Effectiveness	Weighting ¹	Deployable Particulate Sampler		MiniVol™	
		Score	Weighting x Score	Score	Weighting x Score
24-hour Average Concentration	0.60	2.0	1.2	2.0	1.2
Mass	0.40	3.0	1.2	2.0	0.8
	Total		2.4		2.0

¹ The assigned weighting value (0.0 - 1.0) reflects the criteria's importance in the sampler's ability to complete the Army's sampling mission. Highest total value supports best overall course of action.

Table 3-4. Decision matrix for suitability of the Deployable Particulate Sampler and the MiniVol™.

Criteria: Suitability	Weighting ¹	Deployable Particulate Sampler		MiniVol™	
		Score	Weighting x Score	Score	Weighting x Score
Reliability	0.4	4.0	1.6	2.0	0.8
Maintainability	0.3	5.0	1.5	3.0	0.9
Interoperability/ Compatibility	0.0	4.0	0.0	4.0	0.0
Training/ Documentation	0.2	3.0	0.6	3.0	0.6
Logistics Support/ Safety	0.1	4.0	0.4	3.0	0.3
	Total		4.1		2.6

¹ The assigned weighting value (0.0 - 1.0) reflects the criteria's importance in the sampler's ability to complete the Army's sampling mission. Highest total value supports best overall course of action.

Table 3-5. Decision matrix for performance of the Deployable Particulate Sampler and the MiniVol™.

Criteria: Performance	Weighting ¹	Deployable Particulate Sampler		MiniVol™	
		Score	Weighting x Score	Score	Weighting x Score
Flow Rate	1.0	4.0	0.4	2.0	0.2
Size/Weight	0.9	4.0	3.6	2.0	1.8
	Total		4.0		2.0

¹ The assigned weighting value (0.0 - 1.0) reflects the criteria's importance in the sampler's ability to complete the Army's sampling mission. Highest total value supports best overall course of action.

Table 3-6. Final decision matrix for the Deployable Particulate Sampler and the MiniVolTM.

Criteria	Weighting ¹	Deployable Particulate Sampler		MiniVol TM	
		Score	Weighting x Score	Score	Weighting x Score
Effectiveness	0.3	2.4	0.7	2.0	0.6
Suitability	0.4	4.1	1.6	2.6	1.0
Performance	0.3	4.0	1.2	2.0	0.6
	Total		3.5		2.2

¹ The assigned weighting value (0.0 - 1.0) reflects the criteria's importance in the sampler's ability to complete the Army's sampling mission. Highest total value supports best overall course of action.

Table 3-7. Mean time between failure rates

Sampler	Operating Minutes	Operating Hours	Operating Failures	MTBF
MiniVol™	119,645	1994.1	13	1:153 hrs
Deployable Particulate Sampler	119,645	1994.1	2	1:997 hrs

¹Mean time between failures is the ratio of failures to operating hours.

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CHAPTER 4

FUTURE RESEARCH

Overview

The DPS has been shown to have potential in fulfilling the U.S. Army's need for a deployable PM sampler. The MinivolTM is an established system that has performed well over the years at the PM₁₀ level. However, further research on the MinivolTM at the PM_{2.5} level should be conducted to support its deployment as a PM_{2.5} sampler. Completion of the following additional research is recommended to adequately determine which PM sampler will better serve the needs of the U.S. Army at the PM_{2.5} level.

DPS verses an EPA Compendium Method

Research comparing the DPS to an EPA compendium method at the PM_{2.5} level would provide valuable insight as to the quality and correlation of the DPS sampler at that PM sampling level. This would allow us to better correlate our data to the EPA standards and could provide for a better communication of risk.

Particulate Load Limits

Research to establish PM operational upper load limits for both systems at the PM_{2.5} level should be performed. This is significant for operations where the samplers may be exposed to moderate-severe dust storms which have the potential to attribute to impactor overload; thereby, allowing selection of incorrect PM size. Knowledge of sampler upper load limits may encourage development of standard operating procedures (SOP) designed to identify future sampling episodes likely to result in sample overload.

The SOP may also serve as a guide for operators in determining when sampling should be discontinued as a result of potential sampler overload.

Challenge Tests

Field testing provided valuable insight as to sampler deployability. Conducting system challenge tests in a controlled environment at a known concentration of PM would provide valuable information regarding the range limits, accuracy, precision, repeatability, and identification of possible conditions which may significantly impact the samples. Completion of this research on the limits and characteristics of the equipment would provide us with an increased level of trust in our samples and methods, and provide a potential explanation for future suspect samples.

Impaction

Questions have arisen regarding the impaction velocity of the MiniVolTM sampler and of subsequent PM mass loss from the filter media. An analysis of the MiniVolTM design of a two-impactor head design used for testing PM_{2.5} should be performed. The impaction velocity of the two-impactor head design may not adequately capture the PM because of the existence of a potentially turbulent airflow within the two-impactor head assembly. If the potential error created by the impaction velocity can be eliminated, confidence in the MiniVolTM PM_{2.5} sampling ability would be increased and other potential sources of error could be pursued.

Additional Filter Analysis

The 47mm QMA filters may be analyzed for additional compounds of interest post gravimetric analysis. Research should be conducted to determine the feasibility of capturing, extracting, and analyzing additional compounds using the 47mm QMA filter. Potential compounds of interest may be VOC's, PAH's, energetics, toxic metals, and radiologicals. More compounds of interest are sure to be found over time and will need to be evaluated on a case by case basis as to their ability to be sampled on this filter.

Analysis of DPS pre-greased impactor disks

The DPS pre-greased impactor disks are currently being disposed of at the sampling sites. Additional research protocols or SOPs aimed at analyzing the pre-greased impactor disks for contaminants of concern may yield valuable information that is currently being discarded. Analysis of these DPS pre-greased impactor disks for contaminants of concern may assist in further defining Service Member exposures. Furthermore, it would require minimal additional effort during sampling, but would require additional laboratory analysis as each contaminant of concern would need to be analyzed for its presence.

Summary

Research in these identified areas would (1) serve to greatly expand our understanding of and trust in the systems, (2) improve data collection methodology, and subsequently (3) enhance exposure data collection. Completion of this recommended

additional research could significantly increase our ability to protect our deployed forces by minimizing exposure to potentially hazardous environmental exposures.

CHAPTER 5

CONCLUSION

The research described in this thesis evaluated both systems at the PM_{2.5} sampling level in terms of effectiveness, suitability, and performance. The findings of this research, performed in partial fulfillment of the requirements for the degree of Master of Science in Public Health, support the conclusion that the DPS is the better choice of the two evaluated systems for Army deployment.

When evaluated in terms of Army Acquisition Policy for measures of effectiveness, suitability, and performance the DPS proved superior in each of these measures and received a final score of (3.5) to the MiniVol™ score of (2.2) out of a potential score of (5.0).

Additional research, as discussed in chapter four, would further improve our understanding of the systems and increase our ability to protect our deployed forces by minimizing exposure to potentially hazardous environmental exposures.

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